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SCATTERING PHYSICS IN MICROWAVE SIGNATURES OF SEA ICE: A FOCUSSED INVESTIGATION

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OBJECTIVES

The goals of this work have been (1) to achieve a clear, quantitative understanding of the scattering physics behind microwave signatures of geophysically important sea ice types, and (2) to derive microwave remote sensing methods based on, and taking full advantage of, this understanding.

We have worked to understand quantitatively the scattering physics and signature statistics in three important thin ice types that are simulated in the CRRELEX experiment. Specifically, these are bare and snow-covered congelation ice, as well as frazil/pancake ice. In accord with the aims of the Sea Ice Electromagnetics Accelerated Research Initiative, we have also initiated collaboration with investigators in the inverse-modeling community. Specifically, we are helping to develop new inversion methods applicable in the case of electromagnetically-lossy media such as sea ice (in collaboration with J. Sylvester). We have begun to apply these methods to vertical incidence wideband microwave reflectivity data acquired as part of the CRRELEX experiment.

APPROACH

Our approach is characterized by two general principles. First, we avoid signature model fitting; this results in stronger and more robust theoretical progress. Second, we focus our efforts on particular ice types and situations that (1) are of wider importance to Navy needs and (2) in which theoretical tools are near-enough at hand to make substantial progress in the near-term.

Our specific approach can be summarized as follows: In the case of bare congelation sea ice at frequencies 1-10 GHz, we have made substantial theoretical progress and have started to apply our understanding to develop inverse signature models for ice thickness and the vertical profile of permittivity. (This latter work is undertaken in collaboration with J. Sylvester of the University of Washington.)

In the case of snow-covered congelation ice and passive signatures at 10-85 GHz, we have extended theoretical methods based on Dense Medium Radiative Transfer (DMRT) theory and Multi-layer Strong Fluctuation Theory (SFT) to develop demonstrably accurate forward models. Data on snow-covered congelation ice from the 1994 and 1995 CRREL experiments have been valuable in this part of our effort. In the case of pancake ice (which displays much greater surface roughness), we have investigated non-classical rough surface scattering theories suitable for application to pancake ice data from CRRELEX 95.

RESULTS

In connection with snow-covered congelation ice, we have shown that clumping of ice grains in snow can be expected to have a large effect on extinction and scattering in the microwave, and that such effects cannot be approximated accurately using any single "effective ice grain size".

We have also found that collections of densely packed spherical particles exhibit previously unrecognized depolarization and absorption mechanisms. Consider, for simplicity, small particles (ka ≐ 0.1 -1, which can thus be characterized in terms of just their dipole moments). The dipole induced in any given particle depends of the placement of neighbors in the particular realization of the random medium (i.e., random placement of particles). If there are only a few (say, hundreds) of particles within a radius of a few wavelengths from that particle, then mutual particle interactions often force the dipole induced in that particle out of alignment with the incident polarization vector. (This situation stands in contrast to that at longer wavelengths, e.g., those at megahertz frequencies, in which millions of particles typically reside within a wavelength radius of each other -- in that case, there are enough mutual particle interactions to cancel out induced dipole mis-alignments in each and every realization of particle placements.) Depolarized intensity due to this mis-alignment is not cancelled by equally likely counter-aligned dipoles elsewhere in the ensemble, because contributions from regions separated by distances of more than a few wavelengths are, on average, incoherent. Thus the rather high levels of cross-polarized microwave backscattering reported even from fine, rounded-grained snow (for which ka is indeed on the order of 0.1 to 1) may be explicable in these terms. The close packing also leads to higher than expected absorption, which may be significant for emission from snow-covered sea ice.

These new absorption and depolarizing scattering mechanisms in snow-like random media are sensitive to the spacing statistics of scattering particles, and in particular to the pair-distribution function. There have until recently been no estimates of actual pair-distribution functions for the ice particles in air that constitute snow, and thus our ability to test forward models has been limited. We have therefore focussed on the estimation of pair-distribution functions from field data for purposes of model testing. We have adapted methods from the stereological literature not previously used for snow to derive an integral equation that, given snow section data, can be solved for the pair distribution function. We have used Monte Carlo simulation to help estimate the quantity and quality of data necessary to obtain reliable pair distribution function estimates, and have begun to apply the resulting method to actual snow section data. We are thus able to estimate the minimum number and size of snow sections necessary for estimates of the pair distribution function to a given

precision, as well the consequences for scattering calculations of a given imprecision in knowledge of the pair distribution function.

In connection with rough surface from pancake ice, we investigated scattering from rough surfaces with large slopes, considering possible backscattering enhancement and associated pulse-elongation effects.

Our collaboration with Sylvester brought several new results in 1-dimensional inverse theory, as well in application of that theory. First, we have linked the forward theory for polarimetric backscattering from Arctic lead ice to the reflection coefficients used in inverse modeling to estimate dielectric profile properties, including layer (i.e., ice) thickness. This is significant because backscattering is typically the only practical way to do remote sensing, but connections between backscattering the measurements typically required by inverse modelers has not been clear. Second, we have found that polarimetric backscattering data for lossy media (such as sea ice) can eliminate the need for multiple incidence angle data in recovering the dielectric profile or thickness. This is also of considerable practical importance because multi-polarization data are more easily acquired than multiple incidence angle data. Finally, we have contributed to several fundamental results, proved by Sylvester, characterizing and stabilizing the 1-dimensional inverse problem for the first time (anywhere, in connection with any application), as well as a result showing how layer (ice) thickness may be estimated using less information than would be required for a full profile inversion. We are presently testing this theory using nadir-looking, wideband microwave reflectivity data acquired by P. Gogenini (Univ. Kansas) as part of the CRRELEX experiment.

At the same time, the principal investigator has used JPL AIRSAR and SIR-C data to investigate direct estimation of congelation ice thickness in leads in polarimetric SAR imagery at 24 cm wavelength (L-band). This work has shown that polarimetric signatures vary usefully with apparent ice thickness in the range 0-50 cm, and has provided a theoretical model supported by the data, although a lack of surface truth has so far prevented a rigorous test. The theoretical model clearly shows how time sequences of 24 cm polarimetric SAR imagery could be used to estimate sea ice thickness, including of effects of signature statistics also addressed as part of this project. We are therefore particularly excited by the prospects for this work.

PUBLICATIONS WHOLLY OR PARTLY SUPPORTED BY THIS PROJECT

P - Joughin, I.R., D.B. Percival and D.P. Winebrenner, "Maximum Likelihood Estimation of K Distribution Parameters for SAR Data," IEEE Transactions on Geoscience and Remote Sensing, 31:5, 1993.

P - Joughin, I.R., D.P. Winebrenner, and D.B. Percival, "Probability Density Functions for Multilook Polarimetric Signatures," IEEE Transactions on Geoscience and Remote Sensing, 32(3), pp. 562-574, 1994.

P - Grenfell, T.C., M.R. Wensnahan, and D.P. Winebrenner, "Passive Microwave Signatures of Simulated Pancake Ice and Young Pressure Ridges," Remote Sensing Reviews, 9, pp. 51-

64, 1994.

P- Ishimaru, A., L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse Broadening and Two-Frequency Mutual Coherence Function of the Scattered Wave from Rough Surfaces," Waves in Random Media, 4, pp. 139-148, 1994.

P- Ishimaru, A., L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse broadening of enhanced backscattering from rough surfaces," Waves in Random Media, 4, pp. 453-465, 1994.

P- Winebrenner, D.P., L.D. Farmer, and I.R. Joughin, "On the response of polarimetric SAR signatures at 24-cm wavelength to sea ice thickness in Arctic leads," Radio Science, 30:2, pp. 373-402, 1995.

P- Zurk, L.M., L. Tsang, K.H. Ding, and D.P. Winebrenner, "Monte Carlo simulations of the extinction rate of densely packed spheres with clustered and non-clustered geometries," Journal of the Optical Society of America, Vol. 12, No. 8, pp. 1772-1781, August 1995.

P- Sylvester, J., D.P. Winebrenner and F. Glys-Colwell, "Layer-Stripping for the Helmholtz Equation," accepted for publication in the SIAM Journal of Applied Mathematics, 1996.

P- Zurk, L.M., L. Tsang, and D.P. Winebrenner, "Scattering Properities of Dense Media from Monte Carlo Simulations with Application to Active Remote Sensing of Snow", accepted for publication in Radio Science, 1996.

PS - Zurk, L.M., L. Tsang, J. Shi, and R.E. Davis, "Electromagnetic Scattering Calculated from Pair Distribution Functions Retrieved from Planar Snow Sections", submitted to the Transactions on Geoscience and Remote Sensing, 1996.

CONFERENCE PRESENTATIONS

IC - Winebrenner, D.P., T.C. Grenfell, and M.R. Wensnahan, "Temporal Evolution of L-band Polarimetric SAR Observations of Growing Sea Ice in Arctic Leads," presented at the Progress in Electromagnetic Research Symposium (PIERS), Pasadena, CA, 1993.

C - Ding, K.H., L. Tsang, and L. Zurk, "Pair Distribution Functions and Attenuation Rate for Dense Discrete Random Media with Sticky Particles," presented at the Progress in Electromagnetic Research Symposium (PIERS), Pasadena, CA, 1993.

C - Winebrenner, D.P., and J. Sylvester, "Forward and Inverse Modeling for Congelation Ice," presented at the International Geoscience and Remote Sensing Symposium (IGARSS), Pasadena, 1994.

C-Ishimaru, A. L. Ailes-Sengers, P. Phu and D. Winebrenner, "Pulse Broadening and Two-

Frequency Mutual Coherence Function of the Scattered Wave from Rough Surfaces," presented at the National Radio Science Meeting, Boulder, CO, 1994.

C-Ailes-Sengers, L., A. Ishimaru, and D. Winebrenner, "Broadening of Gaussian Pulses Scattered by Rough Surfaces," presented at the IEEE AP-S International Symposium and URSI Radio Science Meeting, Seattle, WA, 1994.

C-Ishimaru, A., L. Ailes-Sengers, P. Phu, Y. Kuga, and D. Winebrenner, "Frequency and Angular Correlations of Waves Scattered by Rough Surfaces," presented at the Progress in Electromagnetics Research Symposium, Noordwijk, the Netherlands, 1994.

C-A. Ishimaru, L. Ailes-Sengers, P. Phu and D. Winebrenner,"Pulse Scattering by Rough Surfaces," presented at the Second International Conference on Ultra-Wideband, Short-Pulse Electromagnetics, New York, 1994.

C- Ishimaru, A., L. Ailes-Sengers, P. Phu, and D. Winebrenner, "Pulse Broadening of the Enhanced Backscattering from Rough Surfaces," with A. Ishimaru,, presented at the International Geoscience and Remote Sensing Symposium, Pasadena, CA, 1994.

C- T.C. Grenfell, M.R. Wensnahan, and D.P. Winebrenner, "Measurement of Microwave Emission from New and Young Saline Ice During the 1993 CRREL Pond Experiment," presented at the International Geoscience and Remote Sensing Symposium, Pasadena, CA, 1994.

C-Zurk, L.M., K.H. Ding, L. Tsang, and D. Winebrenner, "Monte Carlo Simulations of the Extinction Rate of Densely Packed Spheres with Clustered and Un-Clustered Geometries Based on Solution of Maxwell's Equations", presented at the International Geoscience and Remote Sensing Symposium, Pasadena, CA, 1994.

C- "Anomalous Polarization in Backscattering from Arctic Sea Ice at 24 cm Wavelength: Observation and Theory," presented at the Third International Workshop on Radar Polarimetry, Nantes, France, 1995.

C-Zurk, L. M., L. Tsang, and D.P. Winebrenner, "Analysis of the Phase Matrix Obtained from Monte Carlo Simulations of Clustered and Non-Clustered Spheres," presented at the Progress in Electromagnetic Research Symposium, Seattle, WA, 1995

C- Zurk, L.M., L. Tsang, J. Shi, and R.E. Davis, "Electromagnetic Scattering Based on Pair Distribution Functions Retrieved from Planar Snow Sections", presented at the International Geoscience and Remote Sensing Symposium, Lincoln, NE, 1996.

IC-Winebrenner, D.P., "Polarimetric Backscattering at 23 cm Wavelength from Antarctic Lead Ice and Estimation of Ice Thickness", presented at the International Geoscience and Remote Sensing Symposium, Lincoln, NE, 1996.

IC-Winebrenner, D.P., and J. Sylvester, "Inversion of Wideband Microwave Reflectivity to Estimate the Thickness of Arctic Lead-Like Sea Ice", presented at the International Geoscience and Remote Sensing Symposium, Lincoln, NE, 1996.

GRADUATE STUDENTS AND VISITING SCIENTISTS SUPPORTED WHOLLY OR PARTLY BY THIS PROJECT

This project provided research assistantship support, at different times, to three different graduate students. Lynn Sengers was supported for a total of 13 months in 1991 and 1994, and successfully defended her doctoral dissertation in July of 1996. Ian Joughin was supported for 2 months and successfully defended his doctoral dissertation in March of 1995. Lisa Zurk was supported for 17 months in 1993-1996, and successfully defended her doctoral dissertation in December 1995. Dr. Oleg I. Yordanov visited Washington State in 1992 and contributed his expertise to the efforts of Lynn Sengers, and was (with prior permission from the program officer, Charles Luther) compensated with a stipend paid from this project.

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